Investigation of the Properties Of Chilled Cast Iron as a Material For Permanent Magnets

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AN INVESTIGATION OF THE PROPERTIES OF CHILLED CAST IRON AS A MATERIAL FOR PERMANENT MAGNETS

A THESIS

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AN INVESTIGATION of the PROPERTIES

of

CHILLED CAST IRON as a MATERIAL for PERMANENT MAGNETS.

Not all magnetic substances can become magnets permanently. Lodestone, steel, and nickel retain the great part of the magnetism imparted to them. Cast iron and many impure qualities of wrought iron also retain magnetism imperfectly.

The softer and purer a specimen of iron is, the more lightly is its residual magnetism retained.

It is harder to get the magnetism into steel than into iron, and its is harder to get the magnetism out of steel than out of iron; for the steel retains the magnetism once put into it. This power of resisting magnetization, or demagnetization, is sometimes called coercive force; a much better term, due to Lamont, is retentivity. The retentivity of hard tempered steel is great; that of soft wrought iron is very small. The harder the steel, the greater its retentivity.

Form affects retentivity. Elongated forms and those shaped as closed or nearly closed circuits retain their magnetism better than short rods, balls , or cubes. A good permanent magnet must have a residual field of high density and its coercive force must be great. The flux density of the residual field is expressed in kilogausses per sq.cm. or per sq. inch,

and the coercive force is expressed in Gilberts per sq. cm.

The so called permanent magnets are not permanent but their magnetic strength continually decreases until it is to weak to do the work for which it was intended. Many processes of "aging" magnets now in use, but none of these are entirely satisfactory. The damping magnets of wattemeters are treated to special, secret processes by the manufacturers in an attempt to produce a permanent magnet that will not change its strength with use. It is obvious that a magnet of constant strenght is very desirable in electrical instruments such as voltmeters, ammeters and wattemetrs. In the latter if the damping magnets weaken after having once been properly adjusted, the meter will speed up and read too high. Hence, it is obvious that if these instruments are to remain in calibration the strenght of the magnets must not change. The voltmeter tachometer now widely used, furnishes a good illustration of what is desired in a permanent magnet. It consists of a small magneto driven by the motor or engine whose speed we desire to know. So long as the field strength of the "permanent" magnet does not change the voltage generated by the magneto is directly porportional to the speed of the driver. A voltmeter is calibrated to indicate r.p.m. and may be placed at any convenient distant point and connected to the magneto by wires.

The "permanent" fields of these instruments change from day to day so that it is necessary to calibrate them each time they are used, and we are not sure that the fields will not change and give incorrect results during a test of any duration.

In the above statements we have outlined only a few of the many cases where permanent magnets are employed, and where constancy is desirable, and sometimes absolutely essential.

Prof. C. E. Freeman, of Armour Institute of Technology, made some experiments along the lines of this thesis but did not test any of the magnets which he made.

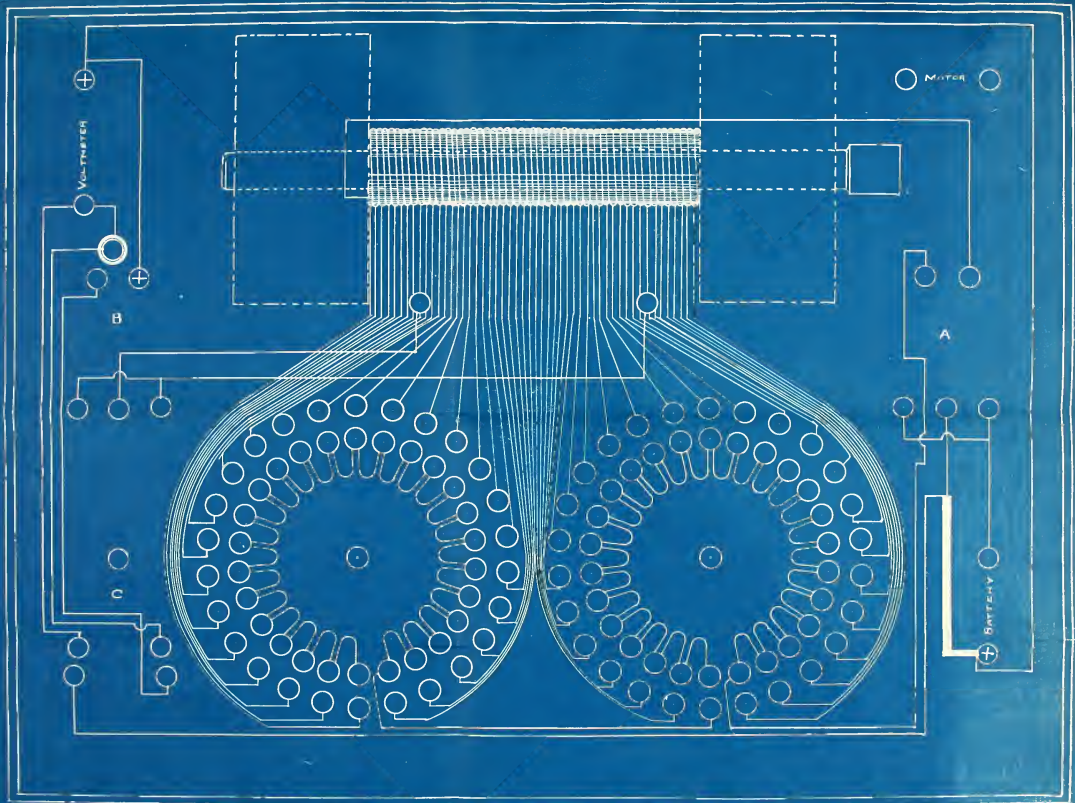
It was, therefore, at his suggestion that we took up this subject.

It is interesting to note here that only those metals which have an atomic weight of 56 to 58 are magnetic, or are capable of being magnetized.

All permanent magnets now in use are made of tempered steel and it is evident that if we are able to make these magnets of cast iron the cost of production will be much reduced.

As we have stated before the retentivity of a magnet seems to depend only on the physical hardness of the material of which it is composed. Hence if we are to make permanent magnets of cast iron some process must be used to harden the iron.

The magnetic density in the specimen under test is indicated by the



ESTERLINE PERMEAMETER

It was with this object in view that we started to work.

The first thing that presented itself was the calibration of the various instruments to be used in this test.

The specimens were to be tested by means of an Esterline Permeameter. A description of this instrument will not be out of place here.

This Permeameter was invented by Prof. Esterline, of Purdue University, and is manufactured by the Central Laboratory Supply Co.,of Lafayette, Ind. The apparatus consists essentially of two poles of high,grade,soft Sweedish, iron, between which rotates an armature would with many turns of fine,silk insulated, wire. The armature was designed to be driven by a small induction motor. An induction was used because of its good regulation, but it was found that the regulation of the ordinary generating unit was not close enough to be used with a scientific instrument. It would probably be sufficiently accurate for commercial purposes, but so for a laboratory instrument. The induction motor was replaced by a small D.C. motor made by the Holtzer-Cabot Company. The specimen to be tested forms the core of the field magnet, and the apparatus is so designed that the E. M. F. developed by the armature is directly porportional to the magnetic flux in the specimen. The magnetic density in the specimen under test is indicated by the

needle of a calibrated Weston voltmeter. The same instrument indicates the magnetizing force applied to the specimen, by simply throwing a single switch. The magnetic circuit is so designed that the reluctance is very low, and is uniformly porportional to the density. The exciting coil consists of a double silk insulated, stranded conductor, with a maximum current carrying capacity of 15 amperes, and the total resistance is such that four cells of a storage battery are sufficient to supply the current. The left hand dial is used to regulate the number of active ampere-turns on the test specimen. The right hand dial is used to compensate for the reluctance of the the magnetic circuit other than that of the test specimen, for the indicated density.

The theory of this instrument is very good, and when properly constructed and calibrated should give accurate results. Upon setting up this instrument we found that the contact points on both dials pressed harder at some points of the circle than others. This variable contact pressure made a very appreciable error in the reading of the instrument. It was also found that the contact resistance of switch "A" and "B" was a variable quanity and the instruments would not read the same in both directions. To remedy this required a different style of contact for both dials and switches. Laminated wire contacts were made and fitted to the instrument by the school

mechanicians. It was also found that many interior contact joits were imperfect and had to be corrected. The brush contact resistance at the commutator was a variable depending upon the condition of the surface of the commutator. We regard this as an inherent defect of the machine as it is almost impossible to keep this resistance constant.
The workmanship of the instrument as it comes from its makers is very poor, but now we believe it to be in the very best possibel condition. A small rheostat for controlling the speed of the motor was made by the mechanician and installed on the base of the motor.
The permeampter was originally calibrated to run at a speed of 1750 r.p.m. For a tuning fork to indicate this speed the fork must have a fractional frequency. It was found to a difficult matter to calibrate a tuning for to the decimal part of a vibration so a standard 100 s.v. tuning for was selected and the permeameter run at 1800 r.p.m. with 15 spots on the card. All these changes, as might be expected, changed the reading of the instrument and made it necessary to calibrate the instrument anew.
A number of ways for calibrating the instrument were considered and rejected because the methods were not absolute. We finally decided to make use of the Ewing ring test which is an absolute method. We cast the ring and bar in one piece as shown in drawing, making the casting much larger than was

really necessary to get rid of skin effects due to casting. The ring was machined to the size shown in drawing and wound with 1200 turns of No. 14 copper wire on the primary and 600 turns No. 28 copper wire on the secondary.

We tested the ring by the Ewing ring method and plotted a B-H and a Permeability curve. Before we made this test it was necessary to calibrate the ballistic galvanometer used. This was done by the Condenser and Standard Solenoid methods. We were very careful to check all readings and we believe the results obtained are quite accurate.

From the straight piece of casting shown in drawing we made a standard test piece for the permeameter. This pece was ground to size very carefully. We assumed that the straight piece would have the same permeabiltiy as the ring.

From the data on the ring test we were able to determine the number of ampere-turns necessary to produce a given flux density. Being able to accurately determine the number of amper-turns on the test specimen at any instant we knew what the voltmeter should indicate, and in this way we were able to calibrate the permeameter.

We used extreme care in doing this work and believe that the only possible source of error is in the assumption that the ring and bar have the same permeabilty.

As these pieces were cast together and have approximately the same amount of material in each, the permeability should not affected by cooling. In making a test with the permeameter we proceeded as follows:

We connected the storage

batteries through a rheostat, to the binding posts marked "battery", taking care to connect the positive terminal of the battery to the positive binding post.
Before placing a bar in the machine, we wined it clean, seeing that clamping bolts were loose. We entered the bar from the right hand side as shown in th diagram.
The was pushed in until the head came within one half inch of the yoke, but not nearer , for the reason that the last half inch is usually tapering. We then set the clamping bolts.

The switch "A" is for reversing the magnetizing current; "B" is to reverse the voltage upon the voltmeter, so that it will always read in the proper direction. When the switch "C" is thrown to the left the readings or the voltmeter indicate the current which is flowing through the machine, the range being from 0 tp 15 amperes.

The left hand dial switch controls the magnetizing turns. These are 100 in number, four turns to the step. The length of the specimen is five inches, so that with ten amperes flowing, the ampere-turns per inch are :-

$$Si = \frac{T \times 10}{5} = 2\,T.$$, where T is the number of turns active. This number of turns for each position of the dial switch is stamped on a ring outside of the dial contacts.

It is customary to use a constant current of 10 amperes, altering the magnetizing force by changing the number of active turns.

The right hand dial contols the compensating turns, to compensate for the reluctance of the circuit other than that of the bar. The figures on the outside of this dial indicate the thousand lines per sq. in. (bar density) for which compensation is made, when the switch is on the respective contacts.

For example to compensate for 50 000 lines per sq. in. , the switch should be set at 50. (This dial is graduated on the basis of ten amperes constant current.)

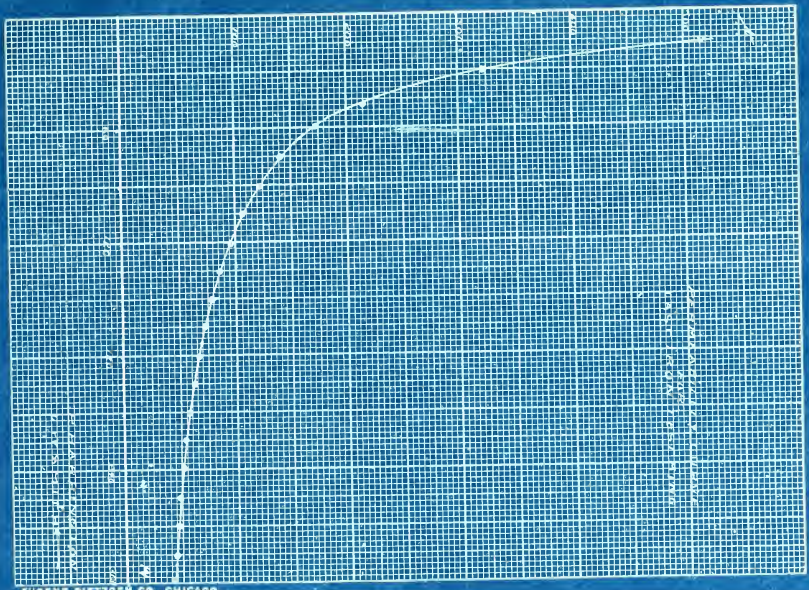
When the switch "C" is thrown to the right, the voltmeter readings indicated the magnetic density in lines per sq. in. , the range being from zero to 150 000 lines per sq. in. If while the switch "C" is thrown to the right, the voltmeter reads backwards the reading was reversed by changing switch "B .
Having placed the bar in the machine and clamped it, we determined whether the bar had any residual magnetism in it or not. We did this by noting whether it gave a voltmeter reading when no current was flowing.
In testing a new bar , we reduced the active turns to zero, thus testing the bar in its vergin state.

If the bar had previously been magnetized and contained residual magnetism, we threw switch "C" to the right, with the active turns equal to zero. We next increased the turns, setting the switch "A" so that the voltmeter reading was reduced as the current or turns were increased. This indicated that the bar was being demagnetized. Before each test we continued this until

little or magnetism remained when the turns active were zero. It is not at all necessary, however, that the bar be thoroughly demagnetized: in fact it is well nigh impossible to thoroughly demagnetize the bar except by heating. We found that a bar which had been previously magnetized was more permeable in one direction than in the other, so that it was found well to take readings with flux in both directions.

Having carefully regulated the speed and adjusted the current to ten amperes, we set the magnetizing and compensating turns to zero, we then proceeded to take readings by moving the left hand dial one step in a clockwise direction whith switch "C" to the right. We reversed the current once or twice using switch "A". We next moved the right hand dial in clockwise direction to position corresponding to the density indicated by the voltmeter. We then read ϕ': we next reversed the current, several times, stopping when switch "A" was in opposite position to that when ϕ' was read. We then read ϕ''. Then $\frac{\phi' \quad \phi''}{2}$ = Correct density, where ϕ' equals flux in one direction, and ϕ'' equals flux in opposite direction.

In testing the specimens for residual density and coercive force, it was not necessary to run through the loop. The values were determined as follows: Let M represent the maximum density, R the residual density and C the coercive force. The bar was placed in the



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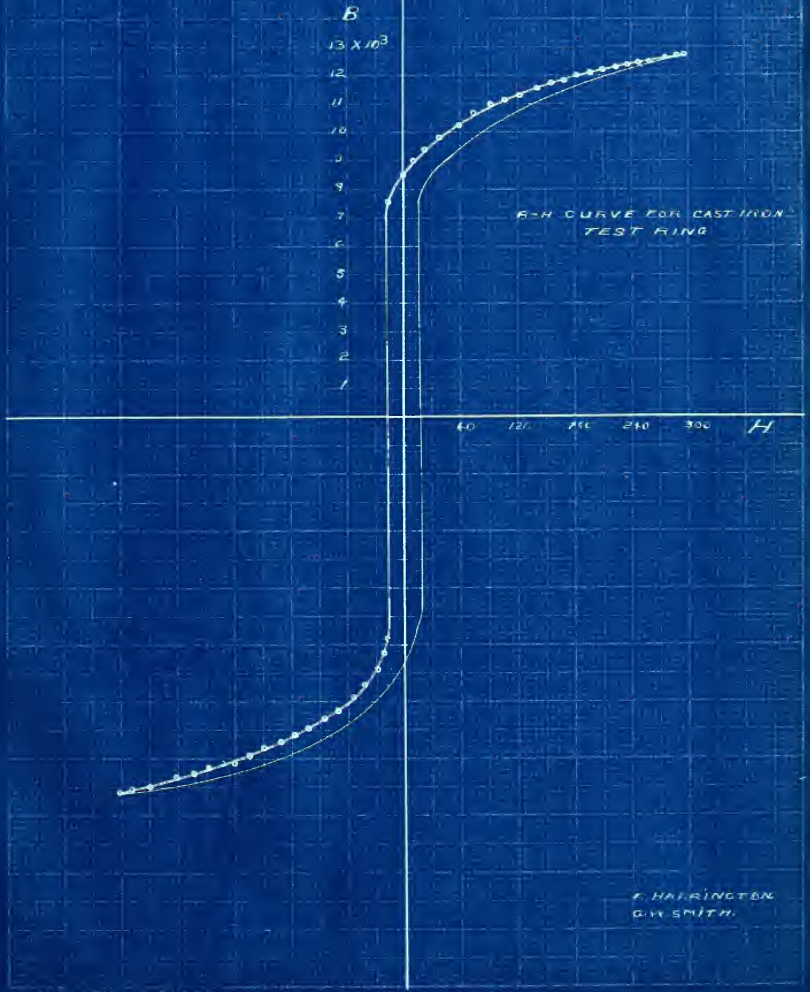
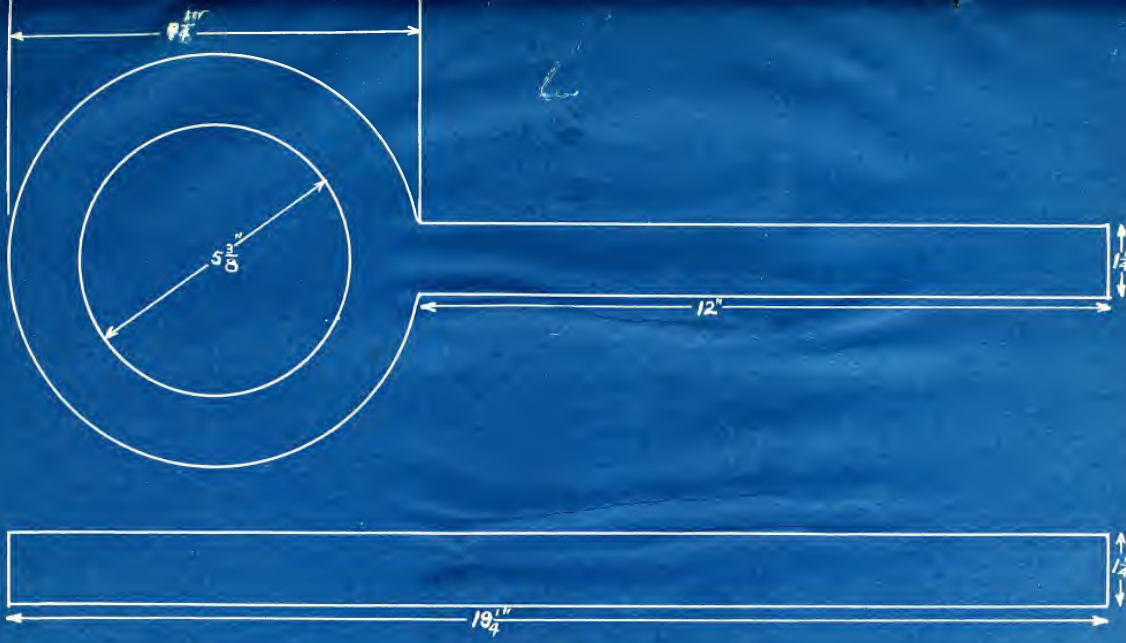

B
13 X 10³
12
11
10
9
8
7
6
5
4
3
2
1
40
120
200
240
300
H
B-H CURVE FOR CAST IRON TEST RING
F. HARRINGTON
G.W. SMITH.

AREA
.2465 in²

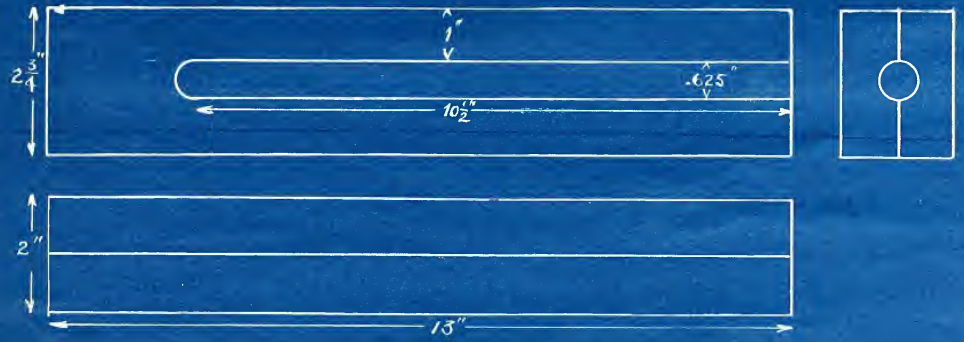
1200 PRIMARY TURNS
600 SECONDARY TURNS
HOT RESISTANCE OF SEC. 33Ω
LENGTH OF RING 1987"

FINISHED SPECIMEN USED FOR
CALIBRATION OF ESTERLINE PERMEAMETER
BY EWING'S RING METHOD
G.W.SMITH
P.HARRINGTON



CAST IRON CASTING USED FOR
CALIBRATION OF ESTERLINE PERMEAMETER
BY EWING'S RING METHOD
SCALE 1/2" = 1"

G.W. SMITH
P. HARRINGTON



CAST IRON CHILL USED FOR
CHILLING CAST IRON SPECIMENS DIRECT FROM CUPOLA

G.W.SMITH
P.HARRINGTON

machine and the full 100 turns applied with proper compensation. We read M and then reduced the turns and compensation to zero and read R. We reversed "A" and increased turns gradually until voltmeter reading was zero. The magnetizing force idicated by position of dial when $\emptyset$ became zero was C, the coercive force. This was reduced to Gilberts per c.m. to be comparable with values of coercive force as usually expressed.

In preparing the test specimens we cast a number rods 5/8 in. in diameter, 12 inches long. These specimens were to be used in making chill test, with water, oil, and mercury. We first experimented with an iron "chill". This iron mould was made in two sections as shown in drawing. The two sections were clamped together with a heavy iron clamp, and the iron poured in at the top. At first it was feared that the iron would blow out of the mould when the hot iron came in contact with the cold surface as quite often happens when this is done. To prevent this the mould was heated to a cherry red heat and the iron poured in it while hot. As the chill was hot the iron cooled slowly and was not hardened except at the surface.
From the results of this experiment we were led to believe the the chilling of cast iron depends entirely upon the time in which the heat is carried away.
We tried pouring the moulten iron into the chill while it was at room temperature, about 70 degrees F.
The iron did not blow as was feared, but some other serious difficulties arose.

The iron was taken hot from the cupola and poured without delay. When the hot iron struck the cold surface of the chill it hardened immediately and prevented the iron from flowing down into the mould as it should. This caused a very imperfect casting and one that was chilled only on the surface. After a number of trials this method was abandoned, only one casting being obtained which we were able to grind to size. All the castings made in this way had soft cores and were of no value as permanent magnets.

The next step was to center all the castings which we wished to chill in oil and mercury. This was made necessary on account of the chilled casting being to hard to drill centers.

After centering the castings it was necessary to determine the melting point of the specimens. For this work we used a Muffle furnace the temperature being indicated by a pyrometer.

The Muffle furnace was of an improved type burning gas with an air blast. The muffle was made of fire clay and prevented the flames from coming in contact with the pieces while being heated.

The temperature was indicated by a Le Chatelier thermo-electric couple pyrometer with milli-voltmeter for temperatures up to 2900 degrees F.
We placed some small pieces in the furnace and raised the temperature until they commenced to melt.

It was found that the iron melted at 2150 degrees F. and that 2100 degrees F. was as high as we could raise the temperature without the metal flowing. We were not able to handle the hot casting as the tongs crushed it out of shape. To remedy this difficulty we cut some pieces of 3/4 in. gas pipe a little longer than the specimens and placed both pipe and specimen in the furnace. The melting point of the gas pipe was higher than that of the cast iron so we were able to handle the casting. We first tried chilling the casting in water after heating it to 2100 degrees F. The casting was warped slightly and was not hardened except for a very thin shell on the out side.

Another specimen was heated to 2100 and dropped in a brine solution. This method failed also as the casting was hardened only on the outside.

A number to tests were made to determine the critical hardening temperature. Tests were made at various temperatures from 1800 degrees to 2100 degrees F. and it was found that at 2050 degrees the pieces were not hardened except on the out side.

Our next experiments were with oil and mercury. We first tried chilling the casting by placing it in mercury in a horizontal position. As the iron floated in the mercury one side was chilled quicker than the other, and the casting warped so much that it always broke in two. The side which first came in contact with the mercury was chilled very hard, while the other side was soft.

We then made a vessel to hold the mercury so that the casting could be inserted in a vertical position. We took a piece of 2" pipe and capped one end. The other end was fitted with a reducing coupling down to one inch. The one inch opening allowed the 3/4" pipe, containing the casting, to be inserted, and the specimen forced endwise into the mercury. This cap was not used in the first attempt and a large part of the mercury was blown out of the pipe. The reducing cap prevented all but the volatilized mercury from escaping.

To harden a piece of cast iron by chilling we proceeded as follows:

The furnace was started and when the pyrometer indicated about 1800 degrees F. a piece of 3/4 " pipe with the cast iron specimen inside was placed in the furnace. The furnace was closed up tight and the full blast turned on until the temperature reached 2100 degrees F. The time required to raise the temperature from 1800 to 2100 degrees was from 45 minuts to one hour, depending upon the quality and pressure of the gas. This was ample time for the pipe and casting to become uniformly heated. When a temperature of 2100 degrees was reached the pipe and casting were removed from the furnace and inserted in the vessel containing the mercury. The casting usually stuck to the sides of the pipe so that we were able to get the pipe in the mercury in a vertical position and the push out the casting with a small iron rod. This was necessary to sink the

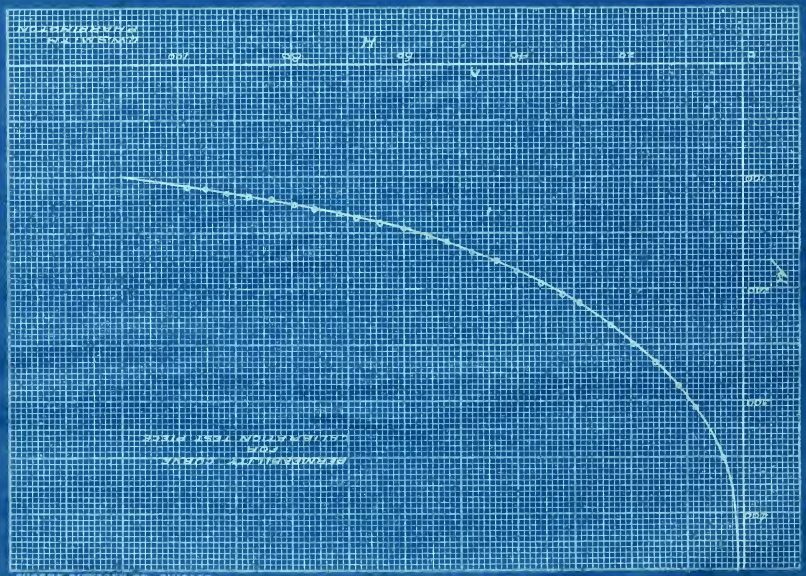
casting in the mercury. The specific heat of the mercury is quite high so that the heat from the casting was conducted away very rapidly. The instant the end of the casting struck the mercury it was chilled and hardened. This uneven cooling caused the casting to warp very badly, in fact so much that it could not be ground to size in the grinding machine.

This method of hardening the casting was quite successful. The castings were hardened all the way t through and were so hard at the center that they would break the edges of the best tempered cold chisel and could not be filed.

Chilling in oil was tried with very good results except that the castings warped as was the case with the mercury. From our experiments we can state the temperatures must be brought just short of the melting point to chill and harded the castings all the way through.

We next tried to make some arrangment to hold the casting straight while it was cooling. We made a "jig" of four pieces of 3/16 " X 5/8" strap iron. We ground the edges that were to come in contact with the casting, to a knife edge. These pieces were held rigid by two cast iron heads. The "jig" was just large enough to make a snug fit on the casting. This piece of apparatus was then placed in the mercury and held down by the cap on the pipe.

The pieces were heated and inserted as before but we did obtain any better results. It was found that when the end of the



EUGENE DIETZGEN CO., CHICAGO.

casting struck the mercury it would warp before the rest of the casting could be forced into the jig.

After making a large number of attempts to get a straight and well hardened casting we forced to give up the attempt. Out of all the pieces we hardened only one was straight enough to be ground at all and this piece was not hardened as well as some of the other castings. The hardened castings were covered with an amalgam of iron and mercury to a depth of about 1/32 ". This amalgam was white in color and very hard. All the pieces were very brittle after hardening but we did not have any trouble with the specimens cracking as was expected.

We calibtated the permeameter and found the constant to be .917. The machine as it stands reads high and must be multiplied by this constant to obtain the correct reading, in lines per sq. in.

We then proceeded to test the chilled specimens for residual magnetism and coercive force.

In order to obtain some comparative tests we tempered some tool steel specimens and tested them for residual magnetism and coercive force. The specimens were raised to a temperature of 1450 degrees F. and tempered in oil. The specimens which were chilled in the cast iron mould did not show much better results than ordinary cast iron. The tempered steel specimens showed a maximun flux about three times that of the specimens chilled in mercury and about twice that of the specimens chilled in the cast iron mould.

The residual magnetism of the tempered specimens was nearly three times that of the specimens chilled in mercury, while the residual magnetism of the specimen made in the iron mould was neary equal to that of the tempered specimens.

On the other hand the coercive force of the chilled cast iron specimens was more than twice that of the tempered specimens. The coercive force of the specimen chilled in the iron mould was slighty greater than that of ordinary cast iron.

Foster and Porter in their "Electricity and magnetism make the followinf statement.

"The coercive force of steel is much greater than that of cast iron. It increases with the porportion of carbon, but it is increased more particularly by the presence of certain metals. Chromium-steel or steel containing one percent of chromium has a coercive force of 40: steel containing three percent of tungsten has a coercive force of 51".

The values given above are for H the magnetizing force where $H = \frac{4\pi N I}{10 L}$, where N I is the ampere turns and L is the length of the magnetic circuit is centimeters. I equals the current in amperes.

It was found that the coercive force of the specimen chilled in mercury was 52.78.

This specimen was heated to a temperature of 2100 degrees F. and treated as described previously.

From these results it is seen that the coercive force of cast iron that has been hardened all the way through is better than that of tungsten, the metal previously having the highest coercive force known. The coercive force is a very essential quality of a permanent magnet. It will be noticed that the residual magnetism was not as high in the cast iron as in the steel but we think that this could be increased by raising the magnetizing force very high. When this is done we feel confident that magnets made of chilled cast iron will prove more satisfactory than those now made of steel when the cost of production and other factors are considered.

D A T A

For Determination of Constant (K) for Ballistic Galvanometer.

Condenser Method. Capacity 1 m.f.

E.	θ (corrected)	K
5.00	413	.6016 y 10^{-8}
4.75	388	.6120 "
4.50	364	.6175 "
4.25	343	.6190 "
4.00	322	.6200
3.75	301	.6225 "
3.50	286	.6125 "
3.25	260	.6250 "
3.00	239	.6300 "
2.75	219	.6310 "
2.50	198	.6310 "
2.25	178	.6310 "
2.00	157	.6360 "
1.75	141	.6205 "
1.50	121	.6200 "
1.25	101	.6165 "
1.00	81	.6200 "
.75	60	.6210 "
.50	40	.6250 "
.25	20	.6410 "
	Average =	.6225 "

θ was corrected for damping and curvature.

D A T A

For Ewing Ring Magnetic Test for Calibrating Permeameter.

I (amps)	ϑ (mm)	B	H	
10.0	385	12712	299	42.5
9.5	385	12712	284	44.8
9.0	385	12712	268	47.5
8.5	376	12414	254	50.
8.	373	12310	239	51.5
7.5	369	12190	224	54.4
7.0	365	12050	209	57.6
6.5	361	11915	194	61.5
6.0	358	11820	179	66.
5.5	353	11660	164	71.1
5.0	347	11470	149	77.
4.5	344	11370	135	84.2
4.0	338	11170	120	93.
3.5	332	11030	105	105.
3.0	328	10830	89	122
2.5	322	10630	74	144.
2.0	312	10300	59	174.8
1.5	306	10110	47	215.5
1.0	292	9640	30	321.
..6	281	9275	18	515.
0.0	257	8490	00.	000.

Data for Cast Iron Calibration Specimen.

B. (sq. cm.)	H	
502	3.97	350
1630	7.94	310
2320	11.9	295
3910	15.9	266
5320	19.8	250
6100	23.8	234
6800	27.8	216
7350	31.8	214
7450	35.7	190
7700	39.8	177
8050	43.7	169
8450	47.6	162
8770	41.7	155
9360	55.6	154
10000	59.8	153
10120	63.8	146
10380	67.7	139
10540	71.5	135
10700	75.6	129
10900	79.4	125
11000	83.5	121
11300	87.5	118
11350	91.4	114
11500	95.5	110
11700	99.2	109

Constant of Permeameter = .917

Data for Coercive Force and Residual Magnetism of Test Specimens.

No. 1
Tempered Steel.

Maximum density.	Residual Mag.	Coercive Force.
129200	67100	21.75

No. 2, Tempered steel.

125700	67400	21.75

Cast Iron chilled in mercury.

45000	26000	52.73

Cast Iron chilled in iron mould.

89000	51300	16.9